The Precision Analysis
of a Relative Phase-Difference Torque Measurement Unit

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ABSTRACT

Measuring system of new gas turbine engine requires for a deep modification comparing to a measuring system of an engine-prototype. This is important to meet the modern requirements to safe maintenance of GTE and amount of information to be measured for solving the problems of control and diagnostics of GTE. The modification of GTE of indirect reaction inter alia concerns the substitution of old hydro-mechanical torque measuring units (TMU) by the new contactless TMU, which implement the phase metering principle. These modifications usually meet problems with getting the properties of materials, TMU parts are made of. Obtaining the required information about the properties of materials tends to drastic money and time expenses. This problem became the subject of the research. This paper deals with the alternative method of torque measuring algorithm synthesis, which is based on the parametric identification of TMU properties by the test data.

MOTIVATION

Modern requirements to reliability of aircraft engines on one hand, and insufficient real-time measured data for control and diagnostics purposes on the other hand make designers to perfect the measurement systems of engines that are already in maintenance for decades. Above all, the modification of the turboshafts includes the replacement of the hydromechanical torque measurement units by the contactless brethren that implement the phase shift approach. Two main questions each designer faces while solving the replacement problem are the error sources and the overall precision of the measurement unit. The answers on this questions will award with understanding of:

- Does each one toque measurement unit need individual calibration?
- What are the sources that form the final error? Compensation of which error sources makes sense?
- Which portion of power will be unattainable because of the limited precision?

Some questions cannot be answered experimentally, the answering on the other ones leads to increased time and money expenses. Hence, the problem of an analytical approach to the total error analysis of the phase shift torque measurement unit and, in case of the high error level, calibration technic becomes the first row issue for the designers.

CONSTRUCTION AND OPERATION

The vast majority of conventional systems used to measure torque operate by measuring the torsional deflection induced by the applied torque, by either of two methods (IATA, 2017):

- Measurement of the twist angle: The twist angle method of torque measurement generally requires a slender portion of the shaft to enhance the twist and a pair of identical toothed disks attached at opposite ends of the slender portion. The twist angle can be determined from the phase difference between magnetically or optically detected tooth/space patterns on each of the disks. This method generally requires the shaft to be rotating shaft (Jean-Luc Charles Gilbert Frealle, 2013) and (Bodin, 2013).
- Measurement of the surface strain: Changes in surface strain can be measured by piezoresistive strain gages attached to the shaft. These strains are generally too small to be accurately measured directly. Common practice is, therefore, to use four gages arranged in a Wheatstone bridge circuit. With rotating shafts, coupling means, such as rotary transformers, slip rings, or local telemetry, are required to feed the excitation current to the gages and to acquire the signal from the bridge circuit in a non-contacting manner (Kistler, 2017).

Opposite to convenient designs, the new design looks similar to first method, but contra to it has only one sensor.

The mechanical parts of the contactless torque measurement unit are presented in Figure 1. They are a shaft, which transfers the torque, a screen and an inducer. The screen is mounted on the shaft. It is fitted with a negative allowance and pinned to the shaft from side A. There is a small clearance between the shaft and the screen at the side B. The inducer is put on the shaft and pinned to it. Both inducer and screen have eight lugs equally spaced along the circumference. The assembling provides a mounting angle between the screen lug and the inducer lug being equal to φ_{20}.

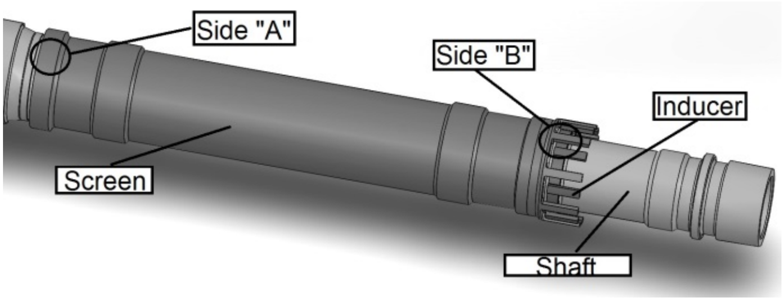

Figure 1 – 3D model of torque measurement unit, which will next be used in the study

When the torque is transmitted from a free turbine to a consumer through the shaft, the side A of the shaft is twisted relatively to the side B at some angle that is proportional to the torque. As the screen is not engaged in the torque transition, the screen lug is displaced relatively to the inducer lug at the same angle. In its turn, the twist angle is proportional to a time interval between the bursts from the inducer and screen lugs when they pass through the electromagnetic field of the TMU sensor. Thus, the torque is determined through this time interval.

TORQUE MEASUREMENT PROCEDURE

Due to the shaft rotation, the inducer and screen lugs pass through the sensor magnetic field. The magnetic lines of force partially stretch in the air and partially – in the lug (Anastasia Kharina, 2014). The more magnetic lines of force stretch in the lug, the higher voltage is. The maximum voltage is achieved when the sensor and the lug are in a common plane. Upon the further movement, the signal starts to decrease due to the sensor magnetic discharge. Roughly we can conclude that the signal of the sensor looks like a sinusoid.

Hence, the next technique can be used to evaluate the torque:

- Register time moment t_1 when the voltage induced by the i^th^ screen lug reaches the boundary, time moment t_2 when the voltage induced by the i^th^ inducer lug reaches the boundary, time moment t_3 when the voltage induced by the (i+1)^th^ screen lug reaches the boundary value.
- Calculate three time intervals:

$$\Delta t_1 = t_2 - t_1 ; \quad \Delta t_2 = t_3 - t_2 ; \quad \Delta t_3 = t_3 - t_1 . \tag{1}$$

In case of a zero torque, the time intervals and the corresponding mounting angles are proportional.

$$\frac{\Delta t_{1\,0}}{\varphi_{1\,0}} = \frac{\Delta t_{2\,0}}{\varphi_{2\,0}} = \frac{\Delta t_{3\,0}}{\varphi_{3\,0}} ; \tag{2}$$

where $\varphi_{1\,0}$ is an angle between the i^{th} screen lug and the i^{th} inducer lug at the zero torque, $\varphi_{2\,0}$ is an angle between the i^{th} inducer lug and the $(i+1)^{th}$ screen lug at the zero torque, $\varphi_{3\,0}$ is an angle between the i^{th} and the $(i+1)^{th}$ screen lug at the zero torque.

- Calculate the current angle φ_2 from the proportion:

$$\frac{\varphi_2}{\Delta t_2} = \frac{\varphi_{3\,0}}{\Delta t_3} , \tag{3}$$

whence

$$\varphi_2 = \frac{\Delta t_2 \cdot \varphi_{3\,0}}{\Delta t_3} = \frac{\Delta t_2 \cdot 45^\circ}{\Delta t_3} . \tag{4}$$

The angle φ_2 of an unloaded shaft is equal to the mounting angle $\varphi_{2\,0}$. As the transferred torque increases, the angle also increases.

Calculate the twist angle as

$$\alpha = \varphi_2 - \varphi_{2\,0} . \tag{5}$$

- Determine the torque according to a torque measurement unit performance:

$$TORQ_i = f\left(\alpha,\ T\right) . \tag{6}$$

SOURCES OF ERROR

One of the questions mentioned in the motivation chapter addressed the sources of error. First, we are going to show you a structure of the error and their impact in the total error. Finally, will make a conclusion about the individual calibration of each one torque measurement unit.

The generic structure of the total error is shown in figure 2. All sources of error can be decomposed into 7 main groups, who are errors caused by the temperature, roughly determined material properties and their change with temperature, errors caused by the centrifugal force, manufacturing and assembling errors and finally measuring method errors.

Then, the total error of torque measurement can be evaluated as

$$\delta_{TOTAL}(TORQ) = \sqrt{\left(\delta_{PhP(T)} + \delta_{AX(T)} + \delta_{RAD\_MB(T)}\right)^2 + \delta_{PhP}^2 + \delta_{PM}^2 + \delta_{LW}^2 + \delta_{ORMB}^2 + \delta_{IRMB}^2 + \delta_{MM}^2} = \sqrt{(6.215 + 0.42 - 1.32)^2 + 1^2 + 0.65^2 + 1.44^2 + 8.08^2 + 5.68^2 + 2.2^2} = 11.572\%. \quad (7)$$

So, definitely this is unacceptable error and each one torque measurement unit needs individual calibration.

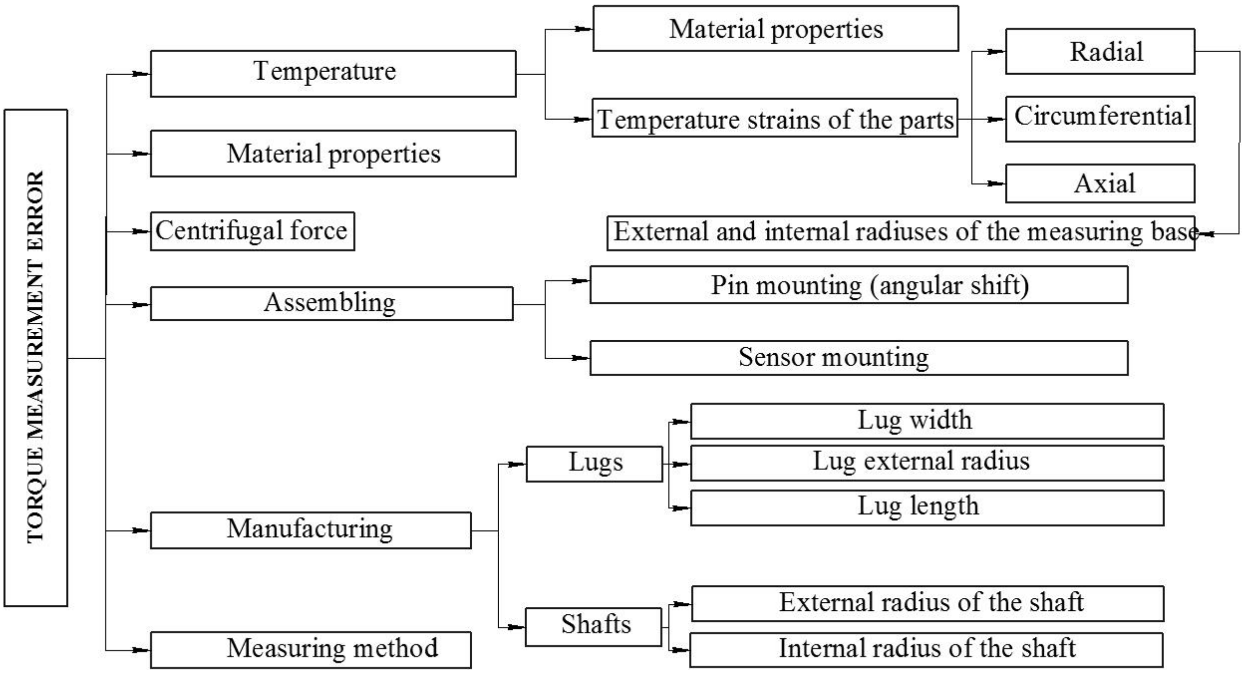

Figure 2 – Main sources of torque measurement error

Each one error has its own impact in the total error, see Table 1.

Table 1 – Analysis results

Source	Error
Material properties	➢ 1% error in material properties leads to 1% measured torque error (δ_{PhP}) ➢ 50°C error in temperature measurement causes up to 1.3% error ($\delta_{PhP(T)}$)
Radial temperature strain	Affects only clearance between the lugs and facing them sensor. Makes no considerable effect on the measured torque
Circumferential temperature strain	No considerable effect

Axial temperature strain ($\delta_{AX(T)}$)	Causes up to 0.42% error in torque measurement because of measuring base elongation (measuring base is the distance between the sections with two pins, see side A and side B in fig. 1)
Centrifugal force	Affects only clearance between the lugs and facing them sensor, making no considerable effect on the measured torque
External and internal radius of the measuring base $\delta_{RAD\_MB(T)}$	50°C error in temperature measurement causes up to –1.32% $$\delta_{RAD\_MB(T)} = \frac{\alpha' - \alpha}{\alpha} = \left(\frac{1}{J'_\rho} - \frac{1}{J_\rho}\right) \cdot J_\rho = = \frac{J_\rho}{J'_\rho} - 1 = \frac{1}{(1+\alpha \cdot T)^4} - 1 = -0.0132.$$
Pin mounting (angular shift) δ_{PM}	Depends on the production perfectness. In the considered case – ±0.65%
Sensor mounting	Makes no effect on a measured torque. Must be considered only to determine the required mounting clearance.
Lug width production error δ_{LW}	If the allowance corresponds to h11 in the standard tolerance grade table, then maximum error caused by this source is 1.44%
Lug external radius	No considerable effect
Lug length	No considerable effect
External radius of the shaft (production allowance is h12) δ_{IRMB}	If the allowance corresponds to h12 grade in the standard tolerance grade table, then maximum error caused by this source is 5.68%
Internal radius of the shaft (production allowance is H12) (δ_{ORMB})	If the allowance corresponds to H12 in the standard tolerance grade table, then maximum error caused by this source is 8.08%
Measuring method (δ_{MM})	2.2% error because of the desecrate measurements

CALIBRATION PROCEDURE

The performance of the measurement unit is:

$$TORQ = A \cdot \alpha + B \cdot T + C \cdot \alpha \cdot T + D, \qquad (8)$$

where A, B, C, D are the parameters to be calibrated.

All parameters may fall into four categories:

- A parameter: The factors that change the resistance to torsion ($G \cdot J_\rho$), which are the inner and outer radiuses of the shaft. The factors of this group depend only on the change in the geometrical parameters of the section.

- B parameter: The factors that depend only on the temperature state of the torque measurement unit parts: the radial, circumferential and axial temperature strains of the parts..
- C parameter: The factors that depend on the temperature state of the torque measurement parts and their resistance to torsion ($G \cdot J_\rho$): the material properties.
- D parameter: The factors of the manufacturing and assembling errors: the pin mounting, the lug width etc.

The stages of the calibration algorithm are presented next.

- Start the engine and accelerate up to an idle mode. The angle $\varphi_{2\ k}$ is determined according to the measurement algorithm presented above. At the same time, a rig bed torque meter measures the torque ($\mathrm{TORQ}_{\mathrm{BED}\ k}$). All measured parameters are then averaged. Calculate the twist angle by the equation

$$\alpha_{\exp} = \varphi_2 - \varphi_{2\ 0}, \tag{9}$$

where $\alpha_{\exp}$ is an experimental twist angle at the mounting angle being equal to $\varphi_{2\ 0}$.

- Evaluate the residual between the calculated twist angle and the measured twist angle

$$\mathrm{RES} = \alpha_{\mathrm{calc}} - \alpha_{\exp} \tag{10}$$

where α_{calc} is a twist angle obtained from the inverse performance of the measurement unit

$$\alpha_{\mathrm{calc}} = \frac{\mathrm{TORQ}_{\mathrm{BED}} - B \cdot T - D}{A + C \cdot T} \tag{11}$$

The performance had been obtained by the finite element analysis of the torque measurement unit 3D model.

- Generate the adjustment to eliminate the residual calculated at the previous step. The adjustment reduces experimental twist angle to calculated twist angle:

$$\mathrm{ADD} = \mathrm{RES}\,. \tag{12}$$

- Introduce the adjustment to the $\varphi_{2\ 0}$ angle. The adjustment is introduced by the change of the mounting angle. New $\varphi_{2\ 0}$ becomes equal to

$$\varphi_{2\ 0\ \mathrm{calibrated}} = \varphi_{2\ 0} - \mathrm{ADD} \tag{13}$$

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- Measure the $\alpha_{\exp}$ by the considered algorithm and $\mathrm{TORQ}_{\mathrm{BED}\ k}$ by the rig bed torque meter at all available modes. The $\varphi_{2\ 0}$ must be equal to $\varphi_{2\ 0\ \mathrm{calibrated}}$.
- Identify performance parameters using least squares method.

The result of the torque measurement unit calibration is an individual performance of the each produced unit.

CONCLUSION

As it was experimentally checked for TV3-117VMA-SBM1V 4E turboshaft, the measurement error of the calibrated torque measurement unit is less than 1% as it is shown in Figure 3.

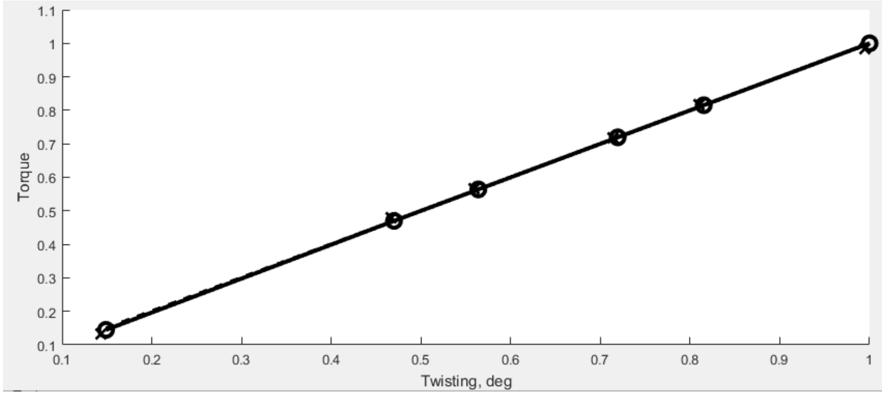

Figure. 3. Theoretical performance (———) vs experimentally obtained measurements (×) with trend line (– – – – –)

The algorithms of calibration and torque determination were implemented in the electronic block of the engine automatic control system. They were verified during the engine rig testing comparing values of the torque determined by the algorithms and directly measured by the rig metering system.

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